Geological Survey
of Canada

Current Research
2001-C2

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2001

Natural Resources Canada Ressources naturelles Canada

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Catalogue No. M44-2001/C2E
ISBN 0-662-29845-4

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101-02817/

Electrical mechanism of mineralized rocks from Giant and Con mine areas, Northwest Territories[1]

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Connell, S., Katsube, T.J., Hunt, P., and Kerswill, J., 2001: Electrical mechanism of mineralized rocks from Giant and Con mine areas, Northwest Territories; Geological Survey of Canada, Current Research 2001-C2, 8 p.

Abstract : Electrical conductivity mechanisms have been determined for five mineralized and unmineralized rock samples (gold-bearing ore, two chlorite schist, and two basalt samples) from the Yellowknife mining district, by analyzing the relationship between rock texture and three-dimensional electrical characteristics. The purpose was to obtain information to help develop efficient exploration strategies in the Yellowknife Mining District.

Results indicate that continuous quartz and calcite layers parallel to foliation act as electrical insulators in schist and basalt, causing very high electrical resistivity values perpendicular to foliation (13 000–14 000 Ω·m). Fine-grained mineral layers accompanied by reasonable amounts of pore space cause moderate pore-fluid connectivity and lower resistivity values (2000–4500 Ω·m) parallel to foliation. Although layers of relatively high concentrated sulphide existed in the gold-bearing ore sample, a lack of good grain-to-grain contacts resulted in low to moderately low resistivity values (10–1000 Ω·m) parallel to foliation (i.e. one to two orders of magnitude lower).

Résumé : On a déterminé les mécanismes de conductivité électrique de cinq échantillons de roches minéralisées et non minéralisées (minerai aurifère, deux échantillons de chloritoschiste et deux échantillons de basalte) provenant du district minier de Yellowknife en analysant la relation qui existe entre la texture de la roche et les caractéristiques électriques tridimensionnelles. Le but de cette étude était d'obtenir des données nécessaires pour élaborer des stratégies d'exploration efficaces dans le district minier de Yellowknife.

Les résultats indiquent que dans le schiste et le basalte, les couches continues de quartz et de calcite orientées dans le sens de la foliation agissent comme des isolants électriques, ce qui donne des valeurs de résistivité électrique très élevée perpendiculairement à la foliation (de 13 000 à 14 000 Ω·m). Des couches de minéraux à grain fin accompagnées de quantités raisonnables d'espaces poreux entraînent une connectivité modérée du fluide interstitiel et des valeurs de résistivité électrique plus faibles (de 2 000 à 4 500 Ω·m) dans les directions parallèles à la foliation. Bien que des couches de sulfures relativement concentrés soient présentes dans le minerai aurifère, l'absence de bons contacts entre les grains donne lieu à des valeurs de résistivité faibles à modérément faibles (de 10 à 1 000 Ω·m) dans les directions parallèles à la foliation (c.-à-d. plus faibles de un à deux ordres de grandeur).

[1] Contribution to the 2000–2001 Yellowknife Mining District, Northwest Territories Exploration Science and Technology (EXTECH-III) Initiative

INTRODUCTION

Electrical conductivity mechanisms have been determined for a suite of five mineralized and unmineralized rock samples from the Giant and Con mines, Yellowknife Mining District, Northwest Territories. The suite consisted of one gold-bearing ore sample from a quartz vein, and two chlorite schist and two basalt samples from host rocks farther from the vein. Our work consisted of analyzing and interpreting data obtained by scanning electron microscope (SEM) examinations and three-dimensional electrical resistivity measurements (Scromeda et al., 2000; Connell et al., 2000b). This follows similar work performed on mineralized and unmineralized sericitic schist samples (Connell et al., 2000a). The purpose of this paper is to document, within the framework of the Yellowknife EXTECH-III Project, results of the electrical conductivity mechanisms determined for the first time on gold-bearing ore, chlorite schist, and basalt samples from the Yellowknife Mining District, and to indicate their implications for interpreting ground and airborne electromagnetic survey data.

METHOD OF INVESTIGATION

The five samples used in this study were selected from a set of ten, which had been previously used for petrophysical characterization (Scromeda et al., 2000; Connell et al., 2000b). This selection was based on representative three-dimensional electrical resistivity characteristics of three rock types (gold-bearing ore, chlorite schist, basalt) from the Yellowknife Mining District. The purpose was to obtain a better understanding of electrical resistivity anisotropic characteristics of the different rock types for application to exploration by electromagnetic methods in the Yellowknife Mining District. Further information on samples, such as depth and lithology, is given in Table 1.

Specimens previously used for electrical resistivity measurements are rectangular blocks, with one side parallel to any foliation present and the other two cut perpendicular to foliation. Detailed visual examinations were also performed (Connell et al., 2000b) and the key features recorded as shown in the block diagrams of Figures 1, 2, 3, 4, and 5. In this study, relevant surfaces of these specimens were polished and prepared for scanning electron microscope (SEM) analysis, which included examination of the sample mineralogy, texture, and fabric of the sulphide and other mineral grains. The use of a SEM for these types of investigations (e.g. Krinsley et al., 1983; White et al., 1984) is increasing and provides useful information for our electrical conductivity mechanism analysis studies.

An image analysis procedure, using a SEM, was used to perform a detailed investigation of the rock texture and its relationship to the three-dimensional electrical resistivities of these samples. A Leica/ Cambridge S-360 scanning electron microscope (SEM) with an Oxford/Link eXL-II energy dispersive X-ray analyzer was used. Operating conditions for the SEM were 20 kV accelerating voltage at a 25 mm working distance. Backscattered electron images (BSI) were produced. A detailed description of the SEM methods and procedures can be found elsewhere (Reed, 1997).

The electrical conductivity model of rocks consisting of thin (0.5–10 mm) multiple layers (Katsube et al., 1997, in press; Connell et al., 1999) characterized by high and low electrical resistivities was used as a guide in this study. In this model, layers with high electrical resistivity consist of electrically insulating minerals (e.g. quartz, feldspar, calcite) with little pore space and result in high bulk electrical resistivity in the direction perpendicular to the layers. Layers with low electrical resistivity consist of either thin, tightly interconnected, electrically conductive minerals (e.g. pyrite, chalcopyrite, magnetite, galena, graphite), or fine-grained mineral grains that accompany reasonable to considerable amounts of pore space. These pore spaces are considered to provide relative to good pore-fluid connectivity, which allows the electrical current to flow along these layers. This results in low bulk electrical resistivities in the directions parallel to the low and high electrical resistivity layers (i.e. parallel to bedding or foliation).

Table 1. Rock descriptions and depths for samples collected from the Giant and Con mines (Yellowknife, Northwest Territories).

Sample number	Stope	Lithology	Sulphide content (%)	ϕ_e (%)	Mean ρ_r (10^3 Ω-m)			Anisotropy (λ)
					α	β	γ	
Giant mine								
MYG-8	370 PS	CS	trace	3.0	13.52 ± 0.39	4.24 ± 0.05	2.07 ± 0.02	6:1
MYG-9	370 PS	Ore	≥10%	2.6	1.69 ± 0.09	0.037 ± 0.003	0.13 ± 0.0	46:1
MYQ-1	Surface	Basalt	trace	0.42	23.77 ± 1.82	12.50 ± 1.16	7.00 ± 0.76	3:1
Con mine								
MYC-6	3148R	Basalt	trace-1%	0.4	3.71 ± 1.48	7.20 ± 2.54	4.47 ± 1.62	2:1
MYC-7	3196R	CS	trace	0.54	13.32 ± 1.68	4.45 ± 0.91	1.94 ± 0.37	7:1

ϕ_e, ρ_r, λ = Effective porosity, electrical resistivity and anisotropy values obtained from other work (Scromeda et al., 2000).
CS = chlorite schist

ANALYTICAL RESULTS AND INTERPRETATION

A schematic representation of a specimen from the basalt sample MYC-6 (Con mine, relatively distant from gold mineralization) is displayed in Figure 1a, showing a faint foliation. The directions of electrical resistivities (ρ_r) are 3710 to 4470 Ω·m and 7200 Ω·m parallel (α-, γ-directions) and perpendicular (β-direction), respectively, to the faint foliation (Fig. 1a). The electrical resistivity anisotropy (λ) of this sample is low (2:1), likely because of the lack of a distinct foliation. This basalt contains quartz, plagioclase, calcite, magnetite, rutile, titanite, pyrite, apatite, chlorite, and chalcopyrite, which were all identified under the SEM (BSI in Fig. 1b, c). The sample is moderately to strongly magnetic, which is likely a signature related to the magnetite associated with a reticular network of rutile crystals (Fig. 1c). Although some electrically conductive minerals (magnetite, titanite, pyrite, apatite, and chalcopyrite) do exist in this sample, they do not contribute to the low electrical resistivity because of their low content and sparse distribution. As the effective porosity (ϕ_E) of this sample is extremely low (0.4%) (Scromeda et al., 2000), the pore water in the interconnected grain boundary pores likely does not contribute much to the electrical conductivity and causes the relatively high ρ_r values (3700–7200 Ω·m) (Katsube and Mareschall, 1993).

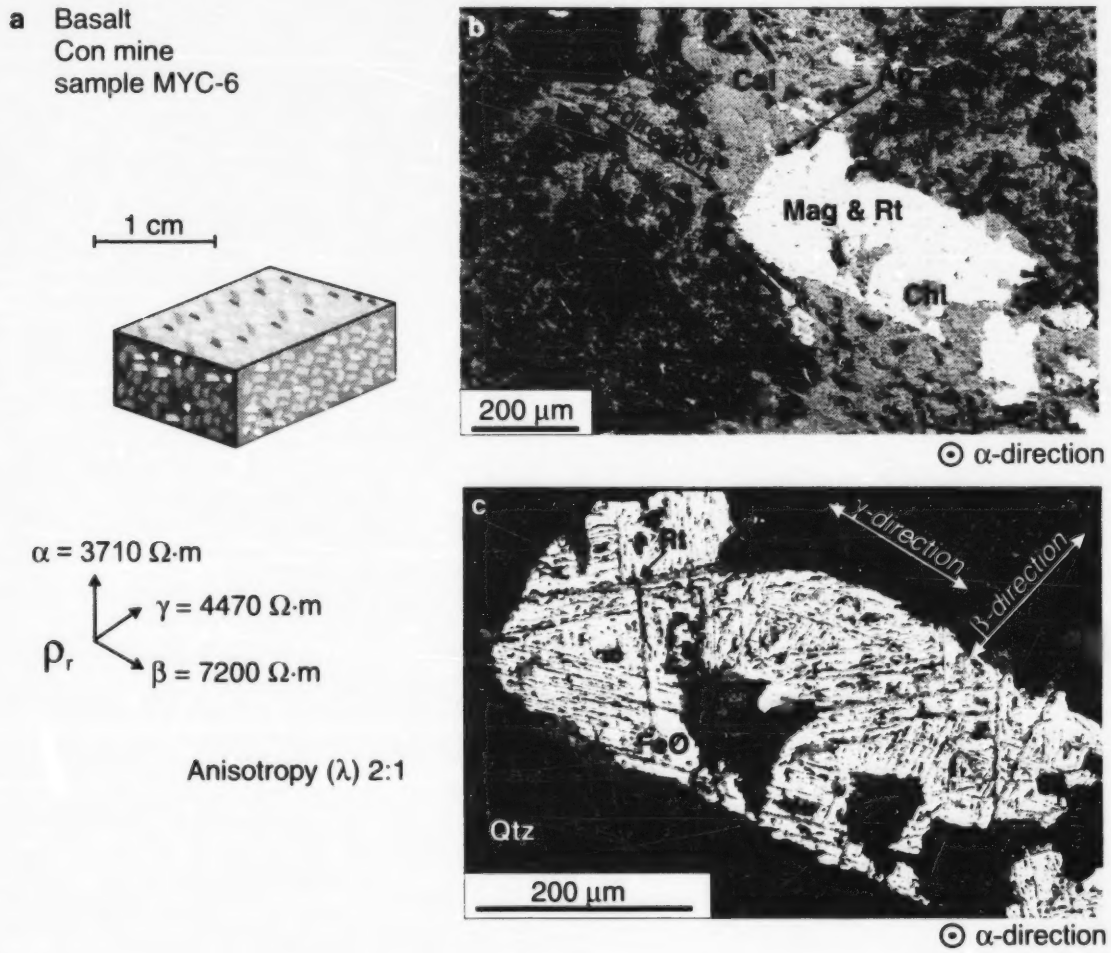

Figure 1. *Schematic presentation of a basalt sample MYC-6 (Con mine) represented by* ***a)*** *a block diagram with sketches of the rock texture and three-dimensional electrical resistivity (ρ_r) and anisotropy (λ) values shown below, and* ***b)*** *and* ***c)*** *scanning electron microscope (SEM) images displayed for surfaces perpendicular to the α-direction. The SEM images (backscattered image, BSI) show the groundmass consisting of quartz (Qtz), chlorite (Chl), and calcite (Cal), with apatite(Ap) and magnetite and rutile (Rt) grain with a reticulate texture.*

A schematic representation of a specimen from the chlorite schist sample MYC-7 (Con mine) is displayed in Figure 2a, showing a strong foliation. The directions of the electrical resistivity values are 1940–4450 Ω·m and 13 320 Ω·m parallel (β-, γ-directions) and perpendicular (α-direction) to foliation, respectively (Fig. 2a). This results in a moderate λ value of 7:1. Chlorite, ankerite, quartz, sericite, apatite, pyrite, plagioclase, rutile, and monazite were identified under SEM, as shown in the BSI (Fig. 2b, c). Both these figures represent specimen surfaces perpendicular to foliation. The high ρ_r value (13 320 Ω·m) in the α-direction perpendicular to foliation is likely due to the fairly continuous layers of quartz, calcite, and rutile grains aligned parallel to foliation, which would act as electrical insulators to the traversing (α-direction) electrical current. The lower ρ_r values of 1940–4450 Ω·m in the (β-, γ-) directions parallel to foliation are likely a result of the fine-grained platy chlorite and sericite grains (Fig. 2b) aligned parallel to foliation, which provide a relatively continuous pore-fluid path for the electrical current to flow in that direction. Although ρ_r values of 1940–4450 Ω·m are not generally considered exceptionally low, they are low (Katsube and Mareschall, 1993) for a rock with a ϕ_E value of 0.54% (Scromeda et al., 2000). The moderately high λ value of this sample is a result of the relatively high and moderate ρ_r values perpendicular and parallel to foliation, respectively. In other words, the fairly continuous layers of quartz that act as insulators to the flow of electrical current result in the high ρ_r values in the direction perpendicular to foliation; the fairly continuous fine-grained platy minerals form a fairly good pore-fluid path resulting in lower ρ_r values in the direction parallel to foliation.

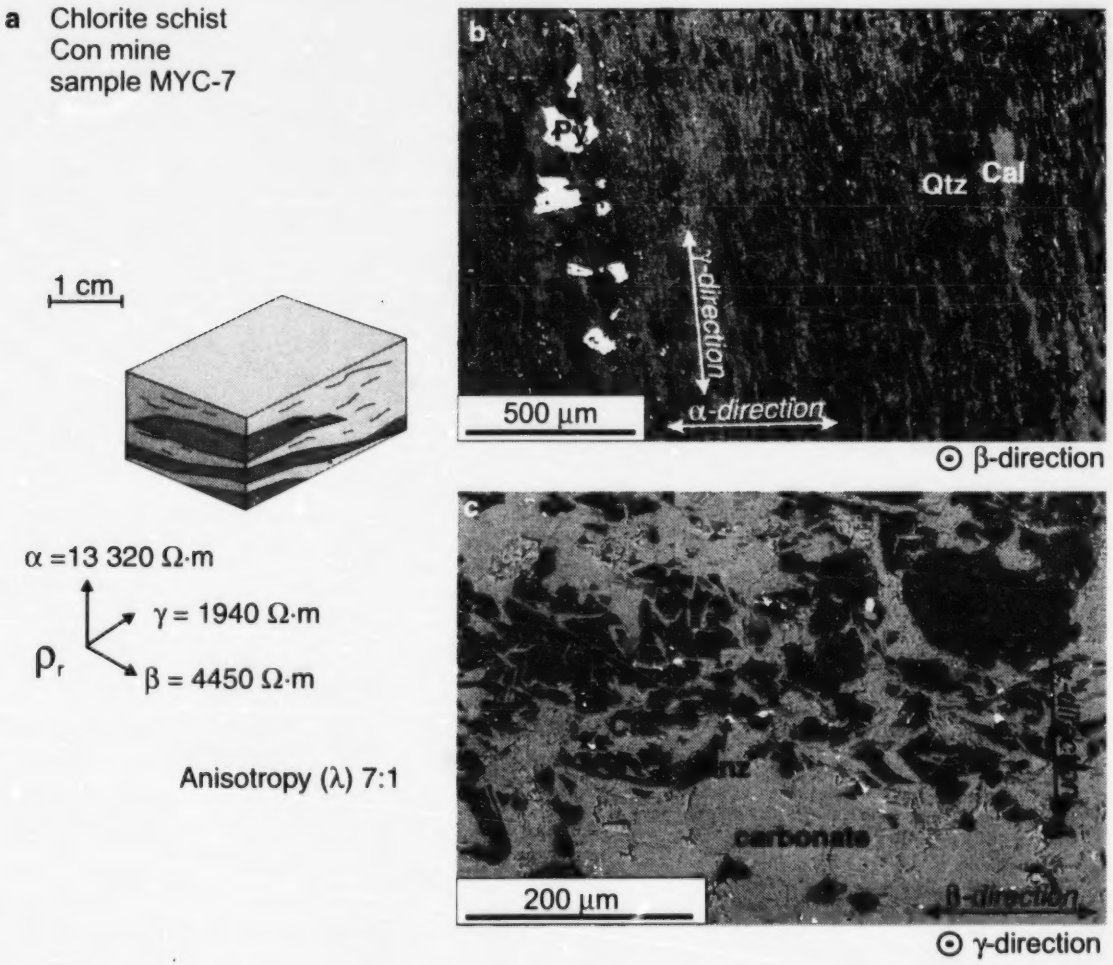

Figure 2. *Schematic presentation of a chlorite schist sample MYC-7 (Con mine) represented by* ***a)*** *a block diagram with sketches of the rock texture and three- dimensional electrical resistivity (*ρ_r*) and anisotropy (λ) values shown below, and SEM images displayed for* ***b)*** *surfaces perpendicular to the β-direction and the* ***c)*** *γ-direction. The SEM images (BSI) show the foliation and minerals identified (pyrite (Py), apatite (Ap), chlorite (Chl), sericite, rutile (Rt), carbonate, monazite (Mnz), quartz (Qtz), and calcite (Cal)).*

A schematic representation of a specimen from another basalt, sample MYQ-1 (Giant mine), is displayed in Figure 3a, showing no visible foliation. Measured ρ_r values of 23 700, 12 500, and 7000 Ω·m were recorded for the α-, β-, and γ-directions, respectively. Amphibole, quartz, plagioclase, calcite, ilmenite, titanite, pyrite, chlorite, and epidote have been identified by BSEI (Fig. 3b, c, d). A calcite vein runs generally perpendicular to the γ-direction, but appears to have no effect on the ρ_r values. A vein usually either reduces the ρ_r values in the direction parallel to the vein or contributes to an increased ρ_r value in the direction perpendicular to the vein; this vein shows neither of these effects. Although this sample shows only a weak foliation, its λ value of 3:1 suggests that a detectable foliation actually exists, likely parallel to the β- and γ-directions. However, no textural characteristics to confirm this suggestion can be found under the SEM. The electrical mechanisms of this sample are, therefore, unclear.

A schematic representation of a specimen from the chlorite schist sample MYG-8 (Giant mine) is displayed in Figure 4a. It has a strong foliation defined by the preferential alignment of platy minerals. The foliation is not as obvious on the polished surface as in hand sample. The ρ_r values recorded range from 2070–4240 Ω·m in the γ- to β-directions parallel to foliation and 13 520 Ω·m in the α-direction perpendicular to foliation. The λ value for this chlorite schist sample is 6:1. This reasonably large λ value is likely a result of the foliation. This sample includes plagioclase, quartz, chlorite, rutile, ankerite, chalcopyrite, pyrite, stibnite, and cobaltite, which were all identified under the SEM (Fig. 4b, c). Although some electrically conductive mineral grains (pyrite) do exist, they do not contribute to the electrical conductivity as they are few and sparsely distributed. The concentrations of flaky chlorite grains aligned parallel to foliation likely form interconnected grain boundary pores for pore water to form electrical conductivity paths, and are likely the reason for that ρ_r values (2070–4240 Ω·m)

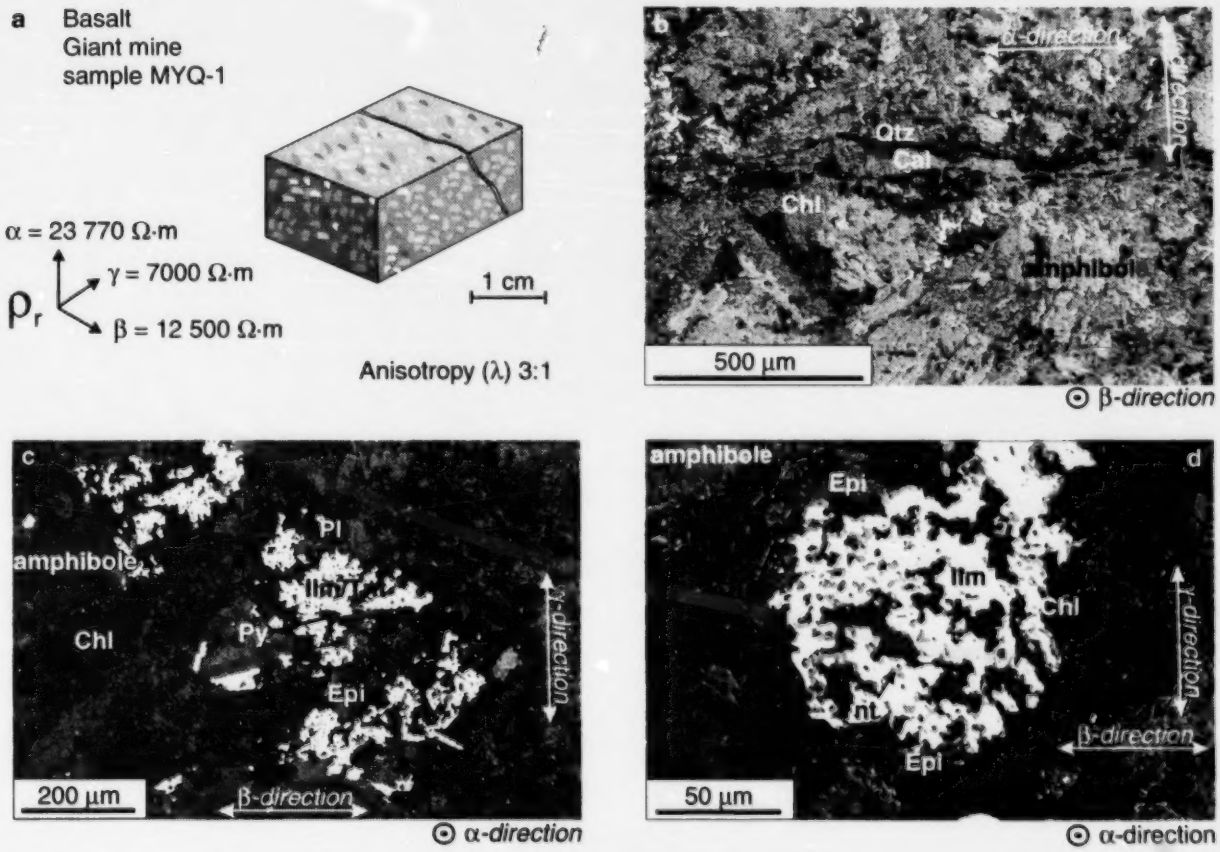

Figure 3. *Schematic presentation of a basalt sample MYQ-1 (Giant mine) represented by* ***a)*** *a block diagram with sketches of the rock texture and three- dimensional electrical resistivity (ρ_r) and anisotropy (λ) values shown below, and SEM images displayed for surfaces perpendicular to* ***b)*** *the β-,* ***c)*** *α-, and d) α-directions. The SEM images (BSI) show the calcite (Cal) vein and minerals identified (chlorite (Chl), amphibole, epidote (Epi), ilmenite (Ilm), titanite (Tnt), plagioclase (Pl), quartz (Qtz), and pyrite (Py)).*

are lower parallel to foliation than perpendicular to it (13 520 Ω·m). The ϕ_E value of this sample is relatively high (3.0%). This supports the possibility that pore-water interconnectivity contributes to the lower ρ_r values.

A schematic representation of a specimen from the ore sample MYG-9 (Giant mine) is displayed in Figure 5a, showing a well defined foliation. The ρ_r values range from 37 Ω·m and 130 Ω·m in the β-, γ- directions parallel to foliation and 1690 Ω·m in the α-direction perpendicular to foliation. This results in a high λ value of 46:1. Quartz, ankerite, chlorite, pyrite, arsenopyrite, stibnite, and sericite were identified under SEM, as shown in the BSI images of Figures 5b, c, and d. Although some layers do have relatively high concentrations of sulphides in the β-direction (Fig. 5b, c) and γ-direction (Fig. 5d), their ρ_r values fall only in the low (10–100 Ω·m) to moderately low resistivity (100–1000 Ω·m) categories and not in the very low resistivity category (<1 Ω·m). This is likely because the interconnectivity of the sulphide grains is poor. The unmineralized, very thin carbonate vein (Fig. 5a, c), which would normally be expected to disrupt the flow of traversing electrical current and cause an increase in ρ_r values in the β-direction, in this case does not show any such effect. The reason for this is unclear. The moderately high ρ_r value (1690 Ω·m) in the α-direction perpendicular to foliation is a result of fairly continuous layers of quartz distributed (Fig. 5b) between the layers of high sulphide concentrations in the β- and γ-directions. The relatively high λ value (46:1) is a result of the moderately high ρ_r value in the direction perpendicular to foliation, and the low to moderately low ρ_r values in the direction parallel to foliation.

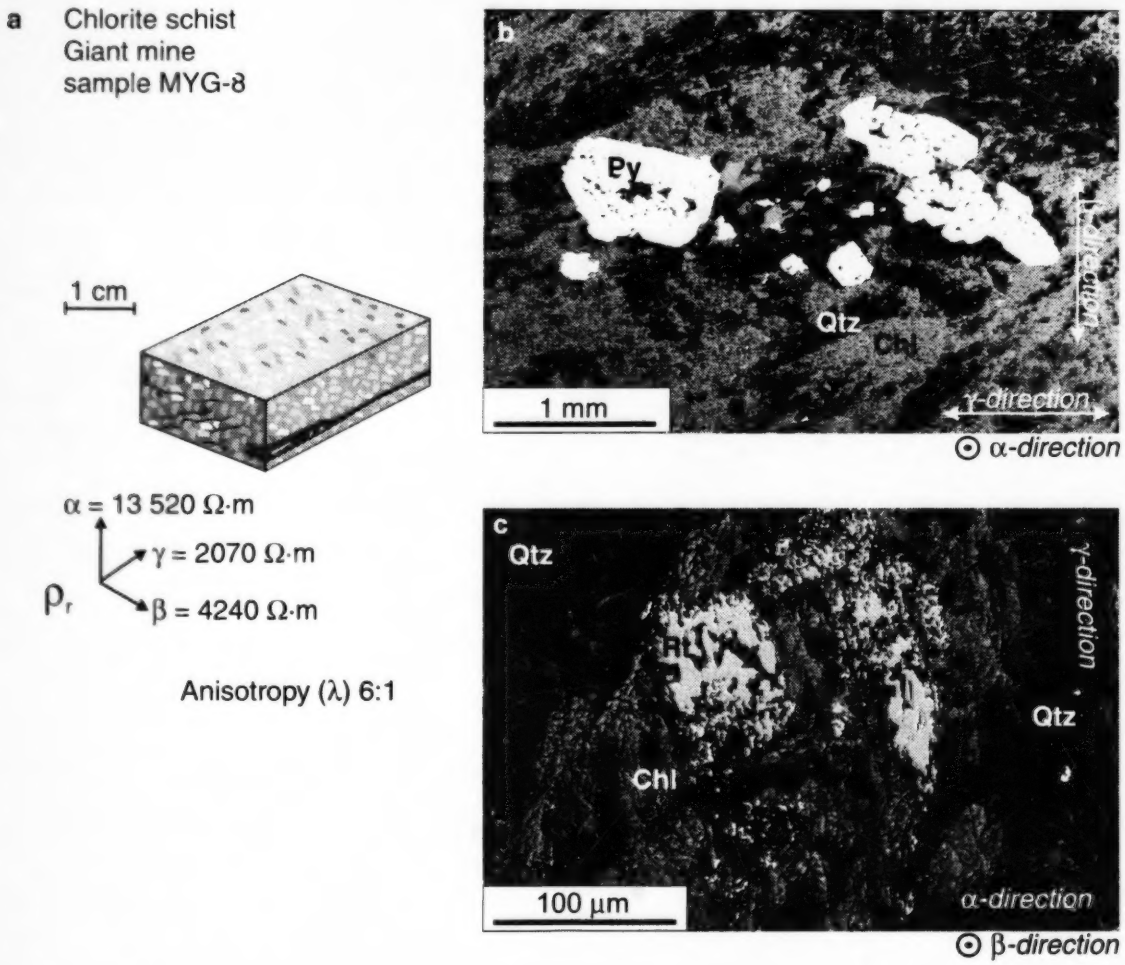

Figure 4. *Schematic presentation of a chlorite schist sample MYG-8 (Giant mine) represented by* ***a)*** *a block diagram with sketches of the rock texture and three-dimensional electrical resistivity (ρ_r) and anisotropy (λ) values shown below, and SEM images displayed for surfaces perpendicular to* ***b)*** *α- and* ***c)*** *β-directions. The SEM images (BSI) show the minerals identified (pyrite (Py), chlorite (Chl), rutile (Rt), and quartz (Qtz)).*

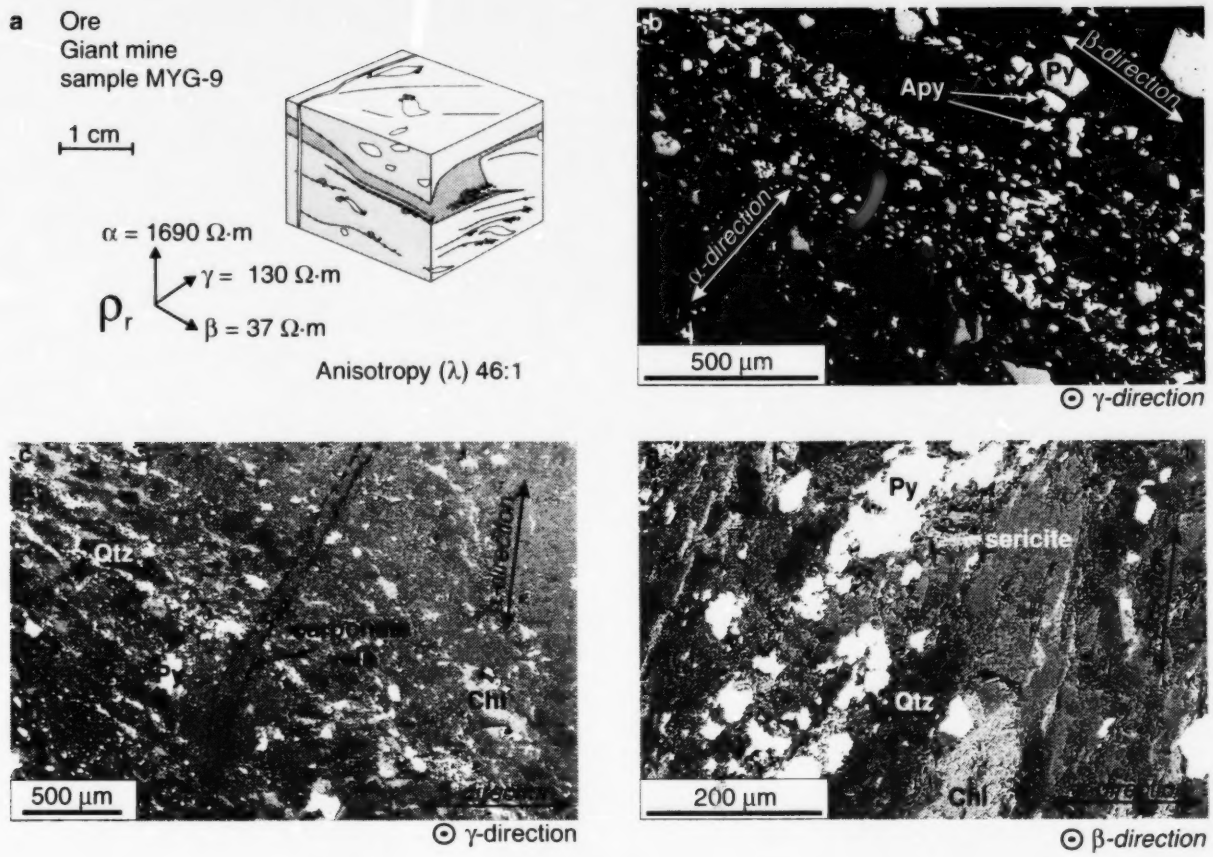

Figure 5. *Schematic presentation of an ore sample MYG-9 (Giant mine) represented by* ***a)*** *a block diagram with sketches of the rock texture and three- dimensional electrical resistivity (ρ_r) and anisotropy (λ) values shown below, and SEM images displayed for surfaces perpendicular to* ***b)*** *and* ***c)*** *(γ- and* ***d)*** *β-directions. The SEM images (BSI) show the distribution of sulphides, carbonate vein, and minerals identified (pyrite (Py), arsenopyrite (Apy), carbonate, chlorite (Chl), sericite, and quartz (Qtz)).*

DISCUSSION AND CONCLUSIONS

The electrical resistivity anisotropy (λ) and electrical resistivity (ρ_r) values for the two basalt samples are in the ranges of 2:1 to 3:1 and 3700 to 24 000 Ω·m (Fig. 3, 5), respectively. The two chlorite schist samples have a λ value in the range of 6:1 to 7:1, and their ρ_r values parallel and perpendicular to foliation are in the ranges of 1900 to 4500 Ω·m and 13 000 to 13 500 Ω·m (Fig. 2, 4), respectively. The gold-bearing ore sample has a λ value of 46:1 and ρ_r values parallel and perpendicular to foliation of 37 to 130 Ω·m and 1700 Ω·m, respectively. The results of this study in conjunction with those previously reported for sericite schist (Connell et al., 2000a, b), indicate a significant decrease in resistivity with increasing proximity to the ore.

The multiple layer electrical conductivity model (Katsube et al., 1997, in press; Connell et al., 1999) explains the electrical conductivity mechanisms of these rocks, with continuous quartz layers acting as insulators to the electrical current flowing perpendicular to foliation (ρ_r =13 000–14 000 Ω·m) and fine-grained mineral layers accompanied by reasonable amounts of pore space (ρ_f =2000–4500 Ω·m) acting as conductive layers. These result in moderate pore-fluid connectivity and lower ρ_r values in the directions parallel to foliation. Although thin (0.5–10 mm) layers with relatively high concentrations of sulphides existed in the gold-bearing ore sample (MYG-9), the lack of good grain-to-grain interconnectivity resulted in only low (10–100 Ω·m) to moderately low resistivity (100–1000 Ω·m) values in the directions parallel to foliation. Good sulphide grain-to-grain connectivity usually results in values of <10 Ω·m in that direction (e.g. Connell et al., 2000a). Although the basalt samples showed some degree of electrical anisotropy (2:1 to 3:1), a visual or SEM examination of the samples showed little layering in the

texture. The electrical resistivity ranges for all of these samples, except those of the gold-bearing ore sample (37–130 Ω·m) in the direction parallel to foliation, are outside the detection limits (>1000 Ω·m) of most commonly used ground and airborne electromagnetic survey systems.

ACKNOWLEDGMENTS

The authors are grateful for the critical review of this paper and for the useful suggestions by B. Kjarsgaard (Mineral Resources Division, Ottawa). This work has been supported by the EXTECH-III (Exploration and Technology) Project, which was initiated in 1999 in the Yellowknife Mining District, Northwest Territories.

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Geological Survey of Canada Project 990032